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HIGH TRANSITION TEMPERATURE SUPERCONDUCTORS -V3GA WIRE DEVELOPM--ETC(U)

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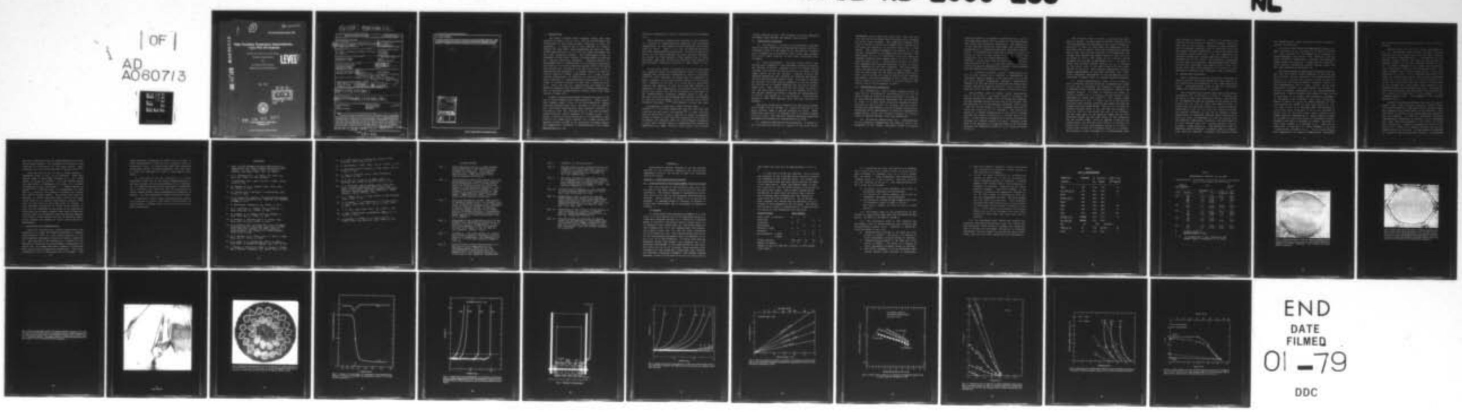

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High Transition Temperature Superconductors —V_3Ga Wire Development

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Increased V_3Ga growth rates resulting from the use of high gallium content V-Ga filaments and Cu-Ga matrix alloys are utilized to improve the critical current density in the superconductor, (J_c) by forming thin layers of V_3Ga at rather low reaction temperatures. Studies of J_c as functions of magnetic field strength and temperature are reported and compared with similar data for experimental Nb_3Sn wires, commercial V_3Ga tapes, and Nb-Ti wire. These data document the superiority of V_3Ga over a broad range of magnetic fields and temperatures. Based on results of these investigations of processing variables, specifications for high current (I_c) multifilament V_3Ga wires were defined and

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20. Abstract (Continued)

an industrial contract for their production was awarded (pertinent specifications appended). Studies of stress effects on I_c have shown these developmental wires resistant to degradation at acceptable stress levels. Further work in this area is recommended for future superconducting applications.

1. SUBC

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I. INTRODUCTION

The Navy's advanced ships concepts require that huge amounts of power (0.5 to 1.0 x 10^6 hp) be available and deliverable to the ships screws, thrusters, or fans for propulsion. A study by CNO in 1973 resulted in a report, "Toward the Year 2000", which emphasized the need for light weight power plants of 10 to 15 lb. per shaft horsepower for the total propulsion system. This requirement serves to highlight current naval interest in superconducting windings for rotating electrical machinery. Although present 6.3 development work is concentrated on dc electrical generators and motors for the main propulsion system (3000 hp initially, then 40,000 hp), proposals have been put forth to use a superconducting generator in a nuclear reactor to meet the overall specific weight requirement of a light weight nuclear power-plant. In addition to rotating machinery, naval interest in superconducting technologies is to be found in systems relating to MHD, CTR, communications, etc.[1] Most, but not all, applications are based on the benefits resulting from the ability of certain superconductors to generate intense magnetic fields (4-20T) over large regions of space (m^3).

Present prototype development programs are based on the use of multifilament Nb-Ti superconductors. These conductors (example shown in Fig. 1) are the products of intense materials programs which were initiated in the mid 1960's. All envisioned applications would benefit directly or indirectly from the availability of new multifilament superconductors which possess (a) higher $J_c(H)$, i.e. higher critical current densities in an applied or self field H, (b) higher $H_{c2}(T)$ values, i.e., higher operational magnetic fields, as well as (c) the option of higher operating temperatures available if superconductors with higher

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transition temperatures could be fabricated as multifilament wire.

Basic materials studies have resulted in the discovery of a variety of superconducting compounds with transition temperatures and high magnetic field properties that exceed those for Nb-Ti. Table I is a list of selected materials and their superconducting properties. With the exception of Nb-Ti, all of these materials are hard, brittle compounds. To utilize the high magnetic field capabilities of these materials, ways must be found to fabricate long lengths of multifilament composites similar to that shown in Fig. 1.

In the early 1970's the question of how one could make such composites when the superconductor itself is a brittle compound was successfully addressed by several investigators[2-4]. They reported the fabrication of composites of Nb_3Sn filaments in a Cu-Sn (bronze) matrix by first forming a composite of Nb rods in a Cu-Sn matrix, physically reducing the composite to fine wire, and then reacting the composite at high temperature. Sn diffuses from the Cu-Sn matrix and reacts with the Nb filament to form Nb_3Sn at the filament-matrix interface. (Example shown in Fig. 2). The past five years has witnessed much activity in attempts to develop multifilament wires by similar solid state diffusion techniques [5-18] with emphasis on Nb_3Sn and V_3Ga.

Our interest in V_3Ga wires stems from our basic studies[19] on the V-Ga system and the fact that V_3Ga was reported by Martinelli and Amenda[20] to have critical current densities, $J_c(H)$, superior to Nb_3Sn in magnetic fields in excess of 13T. Thus the objective of this work is to produce, for eventual naval use, multifilament conductors of V_3Ga with optimum values of superconducting transition temperature T_o, upper critical field $H_{c2}(T)$ and critical

current density $J_c(H,T)$. This program is jointly sponsored by NAVMAT (ZF54-544-009) and NAVSEA (SF54-501-592).

II. FABRICATION TECHNIQUES

A. Introduction: At NRL, multifilamentary composite wires have been fabricated by swaging and drawing V-Ga alloy filaments inside a Cu-Ga sheath to the desired wire diameter. V_3Ga is formed as an interfacial layer around each filament by a solid state reaction in the final isothermal heat treatment.

B. Alloy Preparation: The V-Ga alloys used in our studies were prepared by non-consumable tungsten electrode arc melting in helium. Compacts of pure V (99.9%) and Ga (99.99%) were melted and solidified on the water-cooled copper hearth of the arc furnace. Complete alloying and improved homogeneity were achieved by inverting and remelting the solidified mass several times. To obtain a cylindrical casting, the final melting operation in the arc furnace was carried out on a hearth machined into the top of a split copper mold. When rapidly remelted, the liquid ran down to fill the mold cavity forming a 1.3 cm diameter V-Ga rod. The rod was cleaned by etching, annealed for homogenization at 1050°C, and swaged to 2.7 mm diameter. Intermediate anneals of 900°C were employed after each 50% reduction in diameter.

The Cu-Ga alloys were prepared from high purity metals (Cu-99.999% and Ga-99.99%) by induction melting in an Al_2O_3 crucible under a partial pressure of argon. These alloys were cast as 3.2 cm diameter rods in a ceramic-coated iron chill mold. The rods were surface cleaned by machining, degreased and annealed for homogenization at 750°C.

C. Composite Fabrication and Processing: A cluster of 19 or 30 holes was drilled in a section of the Cu-Ga rod to

accommodate 64 mm long V-Ga alloy rods. Both the V-Ga rods and the Cu-Ga sheath were etched prior to assembly to insure clean surfaces. The composite assembly (V-Ga rods in the Cu-Ga matrix) was capped with a vented Cu-Ga end plug and sealed by an electron beam weld in high vacuum. The composite assembly was reduced to 0.51 mm (20 mil) diameter wire by swaging and wire drawing. The photograph of Fig. 3 illustrates one such composite assembly together with swaged rods and coils of drawn multifilament wires. Intermediate anneals at 500°C were employed after each 37% reduction in area to relieve work hardening in the V-Ga filaments. The Cu-Ga matrix alloy recrystallized during each of these anneals. The wire was then ready for the final isothermal heat treatment, during which the superconducting V_3Ga compound was formed. The photomicrograph of Fig. 4 shows the 4 μm thick layers of V_3Ga formed in a 30-filament wire during a 144 hr heat treatment at 650°C.

III. SUPERCONDUCTING PROPERTIES

(A) Introduction: From a purely pragmatic point of view one is interested in maximizing $J_c(H,T)$ for as large a value of H and T as can be obtained. In order to do this various processing techniques must be evaluated in order to isolate those processing parameters which optimize T_o and $J_c(H,T)$. To achieve this we characterized each developmental wire by standard metallurgical techniques and by measurements of transition temperature, magnetization curves and critical currents for various values of applied magnetic field and temperature.

(B). Transition Temperatures (T_o): Determinations of the transition temperatures were made by using a low frequency (33 Hz) mutual inductance bridge to measure

relative changes in ac magnetic susceptibility, χ , as the wire specimens passed from the normal to the superconducting state with decreasing temperature. The temperature of the specimen during the measurement was continuously determined by a calibrated germanium resistance thermometer. Instrumentation provided a dynamic record of χ verses T, such as that shown in Fi[illegible] 5. Since the transitions into the superconducting st[illegible] a finite breadth ($\sim$ 30 mK wide), the mid-point of [illegible]ansition was designated as T_o. T_o was also determ[illegible]d resistively for several samples and was found in good agreement with the magnetically determined values.

C. Critical Currents $I_c(H,T)$: Measurements of the critical current as a function of temperature and externally applied magnetic field were made in a helium gas flow, variable temperature, cryostat. Temperatures between 4.2K and 20K could be selected and easily maintained. Transverse magnetic fields of up to 13 tesla were applied using the NRL High Magnetic Field Facility.

The procedure used to obtain $I_c(H,T)$ measurements was to fix H and T and then slowly to increase the current through the sample until a voltage was detected. Voltage developed across the wire due to the current flow was measured by a dc differential voltmeter (lower limit $\sim$ 200 nV) and the output of this instrument was used to drive the Y-axis of an X-Y recorder. The X-axis was driven by a voltage proportional to the current flowing through the sample obtained by a series shunt (0.01 ohm). In this manner a sequence of V versus I curves was obtained for selected values of H and T. Typical traces from a wire specimen in an applied field of 10 tesla and covering the temperature range of 9.3 to 10.8K are shown in Fig. 6.

The criteria used to select I_c values from such data are varied. We have used an E-field criterion of 2μ v/cm to designate the beginning of the loss of superconductivity in order to facilitate the comparison of our work with that of others. Since the voltage-probe spacing was 0.5 cm, the $2\,\mu$V/cm criterion is attained when the voltage drop between the probes reaches a value of 1μ V as shown in Fig.6. The value of the current which produces this voltage is designated as I_c. In order to obtain the critical current density J_c, I_c is divided by the total area of the V_3Ga layers in the cross section of the wire. This area was obtained by metallographic measurements of the layer thickness, and electronic planimeter measurements of the peripheries of the individual filaments made on enlarged photomicrographs.

D. Stress Measurements: When a wire is used to wind a solenoid, and this solenoid is subsequently cooled to 4.2K, and is energized, the conductor is subjected to a combined stress arising from mechanical, thermal, and magnetic effects. In order to evaluate the effect of tensile stress on J_c a novel stress cyrostat was developed by Gubser and Jones[21]. This design, shown schematically in Fig. 7, makes use of a cylindrical stainless steel bellows closed by two copper end caps and pressurized with liquid helium. The wire to be tested is inserted through holes in the end caps and soldered in place so that it lies along the axis of the bellows. The end caps serve as the potential leads and the wire extending beyond the end caps serves as the connection for the current leads. Force is applied to the wire by pressurizing the bellows with helium. A typical run starts with a 4.2K zero-pressure series of V versus I curves with values of H ranging from 5 to 13 teslas. The pressure is then increased to a predetermined value

and allowed to stabilize. Traces of V versus I for various H field values are taken in a manner similar to that used at zero stress. Pressure is then increased, and the process repeated. This is continued until the wire shows resistive properties as soon as any current is initiated through the wire. In this apparatus the distance between the voltage leads (the end caps of the bellows) is 1.35 cm. Thus a 1 μ V potential corresponds to an E-field of 0.74 μ V/cm. Representative data obtained from such experiments are shown in Fig. 8 (Ref. 22). Stress data have been gathered on a variety of wire specimens prepared with different heat treatments.

IV RESULTS AND DISCUSSION:

NRL's innovative use of V-Ga alloy filaments in place of pure V (US Patent #4,002,504) has resulted in two significant improvements in the superconducting wires: increased growth rates of the A15 interfacial layers, and increased values of $J_c(H,T)$.

The enhanced V_3Ga growth rates were obtained by increasing the Ga content of both V- filament and Cu-matrix to near their solubility limits. The effects of increasing the gallium contents of the alloys on the growth rate of V_3Ga at 575°C are shown in Fig. 9. Since V_3Ga can be grown faster at a given formation temperature than in the lower Ga content alloys, the desired thickness of V_3Ga can be formed at lower temperatures in reasonable reaction times. Grain size of the V_3Ga layer is dependent on both the growth rate and formation temperature; therefore, the end product is a finer grained V_3Ga that carries greater critical currents. These options have been explored in order to determine those processing variables; such as, composition, need for intermediate anneals, and reaction times

and temperatures, which produce the best values of $J_c(H,T)$, T_o and $H_{c2}(T)$.

The use of lower reaction temperatures results in a small increase in T_o, as shown in the data of Table II. This increase is attributed to an increase in crystallographic long range order resulting from the lower formation temperature, although stoichiometric effects cannot be ruled out. Longer reaction times at a given reaction temperature produce thicker layers and this also produced an increase in T_o.

The superconducting properties of paramount importance are the overall current capacity of the wire and the critical current density in the superconducting phase; i.e., $I_c(H,T)$ and $J_c(H,T)$. Since we are not optimizing the multifilament conductor design in this developmental work on V_3Ga, $J_c(H,T)$ is the most meaningful property for evaluating the effects of various processing parameters on the superconducting properties. Based on present data (Table II shows one set of such data) it is evident that although T_o increases, J_c decreases with increased V_3Ga layer thickness. Figure 10 shows the $J_c(H)$ for three specimens of this wire reacted at 556°C to form V_3Ga layers of 0.8, 1.1, and 1.4 μm. It is believed that this decrease in $J_c(H)$ with layer thickness is due to an increase in grain size of the V_3Ga layer, which results from higher reaction temperatures or longer reaction times. An increase in grain size leads to a decrease in grain-boundary area hence a decrease in overall "pinning" of flux lines leading to a decrease in J_c. Thus one is faced with a trade-off of a small decrease in T_o with a significant increase in J_c. To this end efforts have emphasized low reaction temperatures (500-550°C)

and relatively short reaction times, e.g., 475 hrs. at 500°C.

Selected data of $J_c(T)$ at 6 tesla, presented in Fig. 11, demonstrate the superior current carrying capacity of these V_3Ga wires over the other present day candidate superconductors. A comparison of the critical current density for V_3Ga and Nb_3Sn wires in magnetic fields of 6, 10, and 13 teslas is shown in Fig. 12. An overall assessment of the data, and the processing limitations, leads to the conclusion that a V+8 at%Ga filament and a Cu+17.5 at%Ga matrix is the best composition to use. It is realized that there is a range of compositions which would give acceptable results in the fabrication of multifilament V_3Ga wires, but a decision has been made to concentrate on the V+8at%Ga with some effort being devoted to the V+7at%Ga because of its greater ductility. Accordingly, these are the compositions specified in the contract for the industrial production of long lengths of high filament density wire. (See appendix A for contract specifications).

Present engineering designs call for the use of larger volume high intensity magnetic fields (>10T). The increased physical dimensions and the intense fields will generate high stress levels on the conductor. Thus the effect of stress on the superconducting properties must be assessed. In addition information regarding cryomechanical properties in general is of importance and data have been obtained on the effect of stress upon $J_c(H, 4.2K)$. Figure 8 presented V versus I behavior in a field of 9 teslas observed for various stress levels on the wire. As the sample is stressed, Ic (based on the 0.74 μV/cm criterion) is depressed

and the *transitions from* the *superconducting* to *normal* state become rounded. The rounding is attributed to the opening of microcracks in the V_3Ga layers. Such rounding has also been observed in Nb_3Sn wires[22].

From the data of Fig. 8, the I_c versus stress, σ, dependence shown in Fig. 14 is obtained. These data clearly show a significant decrease in I_c for stress levels in excess of $3x10^8$ Pa. For lower stress values one sees either no dependence of I_c upon σ or a slight increase of I_c with increasing σ. Recent reports on Nb_3Sn[23,24] indicate that an enhancement of some 30% in I_c occurs at low values of σ before the "sharp" fall off at higher values. One should note that the maximum I_c values obtained under stress for Nb_3Sn wires lead to J_c values significantly smaller than that of V_3Ga wires at the *same level of stress.* A more detailed evaluation of these stress effects in V_3Ga will be conducted on the wires to be supplied by Airco under the present contract. The static stress data indicate that for envisioned rotating machine applications static stress effects are not of paramount importance, however the effects of cyclic stress should be ascertained.

V CONCLUSIONS AND RECOMMENDATIONS

The work reported here clearly demonstrates the feasibility of using the "Bronze Technique" to produce multifilament wires of $J_c(H)$ values superior to any other material developed to date for fields in excess of 6T. This has led to the awarding of a contract to the Corporate Research and Development Department of Airco, Inc. to produce 500 meter lengths of multifilament V_3Ga wires of specified geometries. The first "production run" is scheduled for this summer. The

superconducting properties of these wires, as well as their metallurgical structure and integrity, will be assessed by NRL. If these wires meet the standards established by NRL in-house processing, test coils will be wound and evaluated in terms of anticipated naval needs.

In anticipation of the increased I_c of these commercial wires, due to the larger filament density, a new test cryostat for such measurements will be assembled. In addition efforts should be devoted to establishing a suitable test facility for the evaluation of cyclic stress effects and cryo-mechanical properties in general. Ac loss measurements should also be performed.

In addition to this "pure" V_3Ga wire work, efforts are underway to assess the merits and effects of substituting elements such as Al and Ti as a minor third constituent.

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FIGURE CAPTIONS

Fig. 1 Cross-sectional view of a 0.30mm diameter multifilament Nb-Ti superconducting wire produced by Airco, Inc. This conductor contains 517 filaments, 9 μm diameter. Magnification: 400X (Courtesy, Airco Central Research Laboratory).

Fig. 2 Cross-sectional view of the center of a 3.26 mm diameter 67,507 filament Nb_3Sn superconductor produced by Airco, Inc. This view shows the structure of one of 19 Ta-clad modules in this monolithic conductor. Each module contains 3553 Nb filaments, 4.5 μm diameter, in a Cu-10 wt.% Sn matrix. The matrix surrounding the 19-modules is OFHC copper. Magnification: 185X. (Courtesy, Airco Central Research Laboratory).

Fig. 3 V_3Ga wire fabrication at NRL. The partially assembled composite of V-Ga filament rods in the Cu-Ga matrix billet, in the foreground, shows an effort to strengthen the wire with a central Ti-alloy strand. In the background are swaged rods and coils of drawn wire of 30-filament material - intermediate products in producing superconducting wires. Scale: approx. 1:1 (The Cu-Ga billet is 24 mm in diameter.)

Fig. 4 Micrograph of the cross-section of a 0.8 mm diameter wire containing 30-filaments of V-8 at.%Ga in a Cu-17.5 at.%Ga matrix. A 144 hour heat-treatment at 650°C has produced the 4 μm thick layer of V_3Ga on each of the filaments. Marker = 50 μm.

Fig. 5 In-phase, χ', and out-of-phase, χ'', components of the ac magnetic susceptibility as a function of temperature. The temperature at which $\chi' = 0.5$ is the transition temperature, T_o.

Fig. 6 Voltage versus current characteristics of a V_3Ga wire at four temperatures in a transverse magnetic field of 10T. The intersections of these traces with the dashed-line at 1 μV (2μV/cm) are the I_c's of the wire at the respective temperatures.

Fig. 7 Schematic of stress-cryostat.

Fig. 8 Voltage versus current characteristics of a V_3Ga wire at tensile stesses of 0.0 to 4.5 $x10^8$ Pa (0 to 65,250 psi). The magnetic field and temperature were constant: 9T and 4.2K respectively.

Fig. 9 The layer thickness of V_3Ga as a function of the square root of the reaction time for four combinations of filament and matrix alloy compositions (Ga content in at%). The reaction temperature is 575°C.

Fig. 10 Critical current density, J_c, as a function of the transverse magnetic field for three V_3Ga layer thicknesses at 4.2K.

Fig. 11 Comparisons of the J_c values for two NRL multifilament V_3Ga wires, a BNL experimental Nb_3Sn wire (Ref. 6), commercial tapes from Vacuum Metallurgical Co., Ltd. (Ref. 20), and commercial Nb-Ti wire from Imperial Metal Ind., Ltd. (Ref. 20).

Fig. 12 Comparisons of the critical current density of V_3Ga and Nb_3Sn as a function of temperature in transverse magnetic fields of 6, 10, and 13T. Nb_3Sn data from Ref. 6.

Fig. 13 Critical current as a function of tensile stress for two specimens of 30-filament wire (V-8 at.%Ga/Cu-17.5 at%Ga) reacted at 556°C for 116 h to produce 0.85 μm layers of V_3Ga. Test conditions: 4.2K, 9T, E-field criterion of 0.74 μ V/cm.

APPENDIX A

Specification section (Section F) of the contract awarded to the Corporate Research and Development Department of Airco, Inc. by NRL in Sept. 1977 (Contract: N00173-77-C-0312):

SECTION F - DESCRIPTION/SPECIFICATIONS

F-1 SPECIFICATIONS FOR MULTIFILAMENT V-Ga/Cu-Ga WIRES

The long lengths of multifilament V_3Ga wire will be used to wind small magnet coils at NRL for test and evaluation. The shorter lengths of unreacted multifilament wire will be used in NRL materials characterization studies. This contract is Phase I of a continuing program. An expanded Phase II contract is planned in Fiscal Year 1978 budget and is contingent on sponsor's funding.

1.0 General

1.1 Wires containing continuous filaments of a V-Ga alloy in a Cu-Ga matrix are to be fabricated using as a guide NRL's patented process (U. S. Patent No. 4,002,504 dated 11 Jan 1977). The matrix alloy, a Cu-Ga alloy, is to contain 17.7±0.2 atomic pct. Ga. The V-Ga alloys for the filaments will be of two compositions: one containing 7.0±0.2 atomic pct. Ga, and the other containing 8.0 ±0.2 atomic pct. Ga. The cross-sectional area ratio of the bronze-matrix/filaments shall be between 3/1 to 4/1 (i.e. 25 to 20% filaments). To avoid local gallium depletion during V_3Ga growth, the filaments are to be uniformly distributed in the cross-section of the wire. The wires are to be of circular cross-sections with diameters of 0.81±0.01mm and 0.51±0.01mm, each containing 2500-3000 continuous filaments. The average filament diameter in the 0.51 mm wire is to be 4 to 8 μm, and in

the 0.81mm wire they will be approximately 6 to 12 μ m.

1.2 Two sets of wires are required. Set A containing filaments of the V-7at.%Ga alloy, and Set B containing filaments of the V-8at.%Ga alloy. The lengths of the individual wires and other specifications are shown in the table below. These requirements apply to both Set A and Set B. The 500 meter lengths of wire must be one continuous length. The 50 meter lengths may be divided but no piece shall be shorter than 4 meters. The isothermal heat treatments for the "Reacted to V_3Ga" wires will be at $550^oC \pm 5^oC$. Two of the 500 meter lengths, one twisted and one untwisted, will be reacted at this temperature for 100 hours. The remaining 500 meter length of untwisted wire in each set will be reacted at this temperature for 256 hours.

SPECIFICATIONS	REQUIREMENTS				
Twist pitch (1 turn/cm.)	X		X		
Untwisted		X		X	X
Insulated	X	X			
Uninsulated			X	X	X
Reacted to V_3Ga	X	X			
As-drawn			X	X	X
Wire diameter: 0.51mm	X	X	X	X	
0.81mm					X
Length (meters)	500	500	50	50	50
Number of Lengths	1	2	1	1	1

(Length of wire in each set, A and B, is 1650 meters (5413 feet)).

1.3 Quotations are also solicited for an optional set of wires that will contain 24,000 to 25,00 continuous filaments of V-8atomic pct. in a Cu-17.5 atomic pct. Ga matrix. (Same composition and bronze-matrix/ filament ratio as in Set B wires.) This set of wires will be referred to as Set C. The specifications for Set C wires are as follows:

a. 50 meters of 0.81mm diameter wire that is unreacted, untwisted, and uninsulated.

b. 50 meters of 0.51mm diameter wire that is unreacted, untwisted, and uninsulated.

c. 500 meters of twisted 0.51mm diameter wire that is "reacted to V_3Ga" at $500^oC \pm 5^oC$ for 200 hours. (Length of wire in Set C is 600 meters.)

1.4 The metals used in the preparation of the alloys for these wires shall have the following minimum purity: 99.999% Ga, 99.999% Cu, 99.9% V.

1.5 The procedures used in the research and development work on superconducting V_3Ga wires at NRL are described in detail in the attached U. S. Patent NO. 4,002,504 dated 11 Jan. 1977.

a. Homogenization anneal to be used for V-Ga alloys is 1050^oC - 49 hours in a vacuum or inert atmosphere furnace (Argon or Helium).

b. Homogenization anneal to be used for Cu-Ga alloys is 800^oC - 24 hours in a vacuum or inert atmosphere furnace (Argon or Helium).

c. The billet assembly is to be evacuated under vacuum before final sealing is performed.

d. When the composite assembly is being cold-worked the mechanical reduction cannot exceed a 20% reduction in diameter.

e. After the above reduction an intermediate anneal of 500°C for 1 hour in a vacuum or inert atmosphere furnace is required. A second anneal after another 20% or less reduction in diameter is required. (Same as the 1st intermediate anneal). The third anneal in the process of reducing the composite's diameter is to be 50°C higher in temperature than the 1st two intermediate anneals. The third anneal will be 550°C for one hour. This sequence following the above reductions is to be followed with every third anneal at 550°C for one hour. This sequence following the above reductions is to be followed with every third anneal at 550°C until the final wire size is reached.

1.6 The contractor shall define and identify all proposed variations/deviations from the stated NRL specifications, their potential effects, and justification or reason for the change. Variations or different approaches, that are deemed to provide the basic objectives, will be given full evaluation and consideration.

TABLE I

HIGH T_O SUPERCONDUCTORS

COMPOSITION (nominal)	STRUCTURE	T_O (K)	H_{c2}(4.2K) (tesla)	J_c(10T, 4.2K) (10^4 amp/cm^2)
Nb_3Ge	A15	23.3	37.0	10
$Nb_{3.2}[Ge_{.2}Al_{.6}]$	A15	20.7	41.0	30
Nb_3Ga	A15	20.3	33.0	3
$Nb_3[Ga_{.5}Al_{.5}]$	A15	19.0	31.0	
Nb_3Al	A15	18.9	29.5	
Nb_3Sn	A15	18.3	26.0	50
V_3Si	A15	17.1	23.0	9
V_3Ga	A15	15.4	23.6	170
$Pb_{1.0}Mo_{5.1}S_6$	CHEVREL	14.4	51.0	<.1
$Sn_{1.0}Mo_{5.0}S_6$	CHEVREL	13.4	29.0	
NbN	B1	16.0	15.0-29.0	
$Nb[N_{0.7}C_{0.3}]$	B1	17.8	<12.5(?)	10
Nb-Ti	A2	9.1	~12.0	1

TABLE II

SUPERCONDUCTING PROPERTIES OF V_3Ga WIRE

Wire Description: 19 filaments of V-6.1at.%Ga alloy in a Cu-17.5at%Ga matrix. Wire Diameter: 0.81 mm (32 mil.)

Reaction Heat Treatment		V_3Ga			Overall Wire
T(°C)	Time(hr)	Thickness (m)	T_c (K)	J_c* (10^5 amp/cm²)	I_c* (amp)
556	122	0.8	14.71	10.6	54.0
	262	1.1	14.84	7.8	65.3
	400	1.4	14.84	6.3	62.4
	1265	2.5	14.98		D
575	112	1.1	14.75	(7.9)+	55.2
	164	1.3	14.80	(7.3)	60.1
600	40	1.1	14.71	(8.2)	56.9
	64	1.4	14.86	7.1	61.5
	244	2.7	14.93	5.3	87.6
625	64	2.5	14.86		D
	256	5.0	15.02	(2.4)	75.8
650	25	2.5	14.75	(3.0)	47.5
	220	7.5	14.99	(2.0)	97.5

* I_c and J_c: 4.2K, 10T

D specimen damaged in tests.

( )+ J_c estimated from I_c value, assuming the same average filament circumference in all wires.

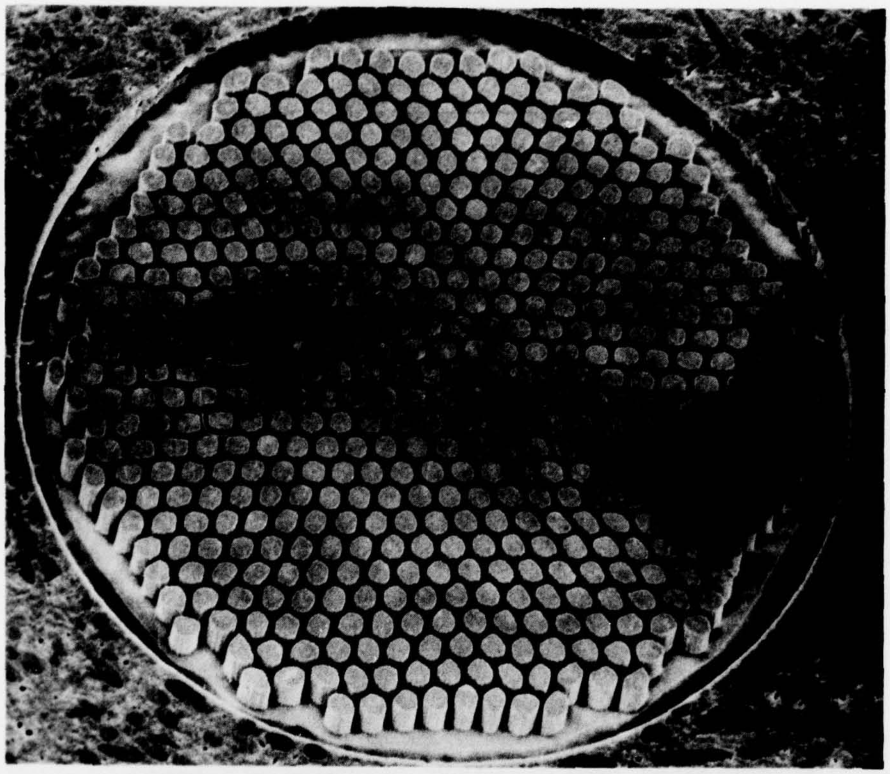


Fig. 1 - Cross-sectional view of a 0.30 mm diameter multifilament Nb-Ti superconducting wire produced by Airco, Inc. This conductor contains 517 filaments, 9 μm diameter. Magnification: 400X (Courtesy, Airco Central Research Laboratory).

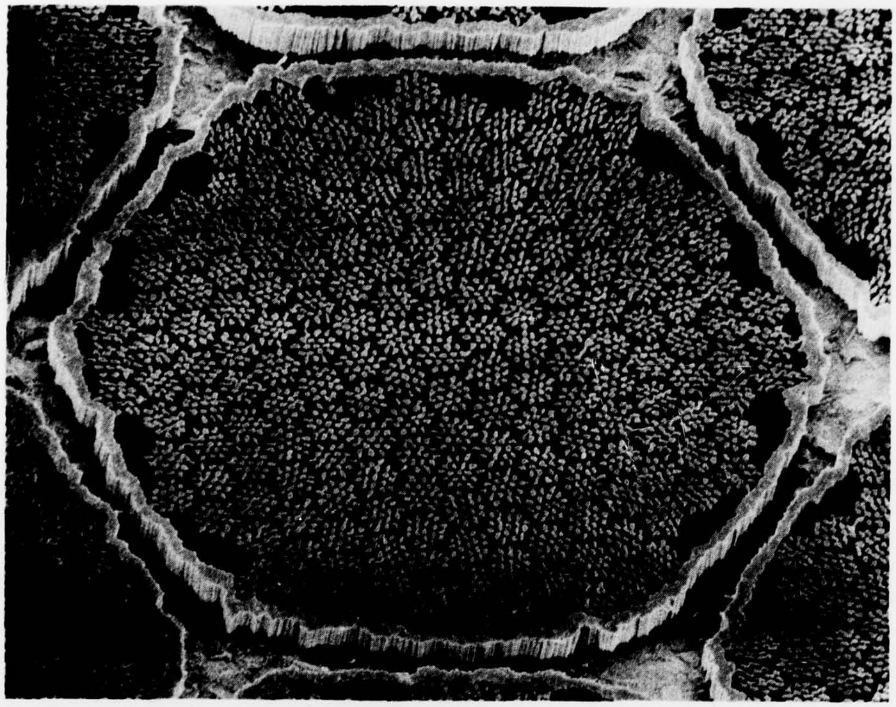
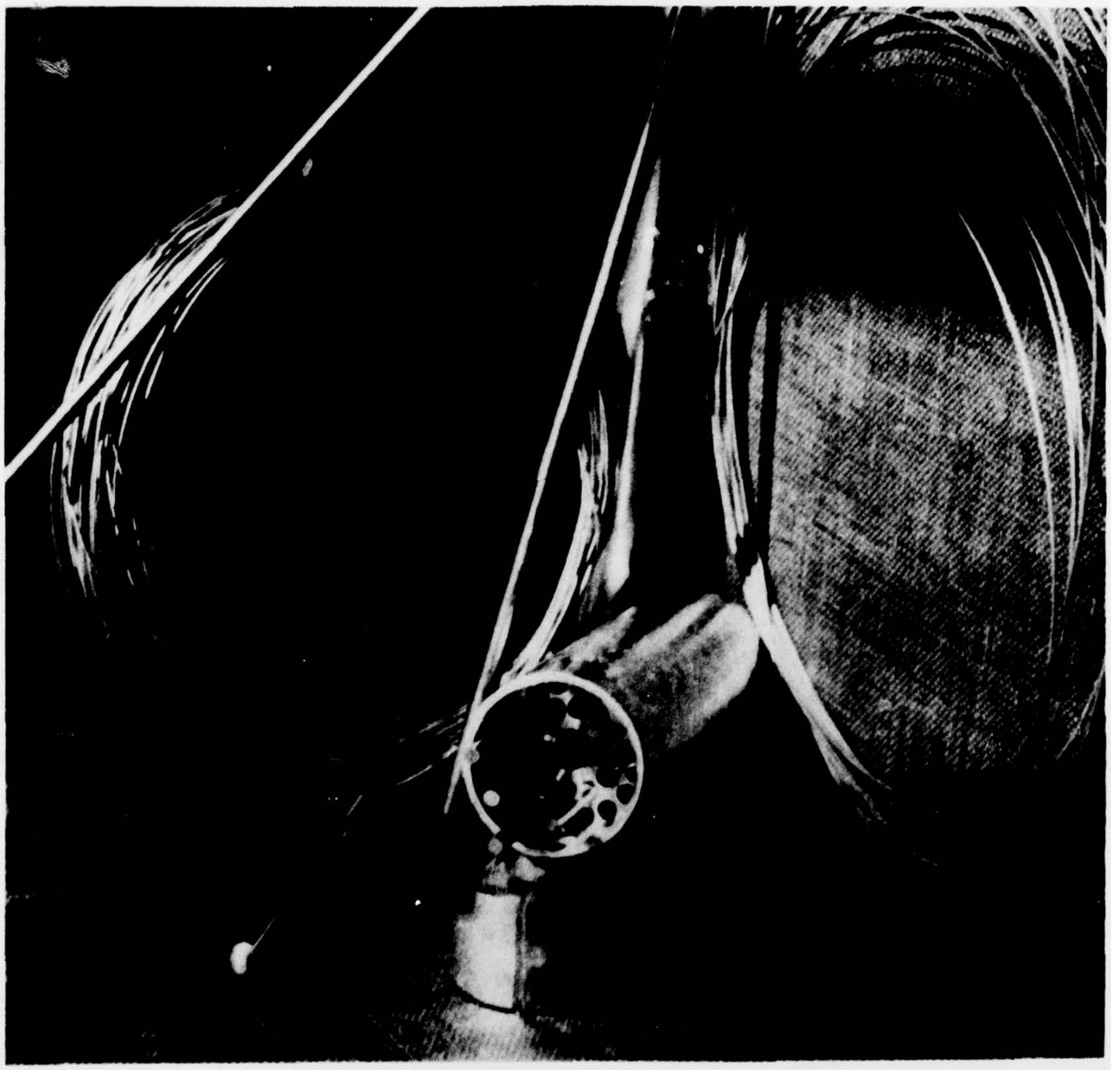


Fig. 2 - Cross-sectional view of the center of a 3.26 mm diameter 67,507 filament Nb_3Sn superconductor produced by Airco, Inc. This view shows the structure of one of 19 Ta-clad modules in this monolithic conductor. Each module contains 3553 Nb filaments, 4.5 μm diameter, in a Cu-10 wt % Sn matrix. The matrix surrounding the 19-modules is OFHC copper. Magnification: 185X. (Courtesy, Airco Central Research Laboratory).

Fig. 3 - V_3Ga wire fabrication at NRL. The partially assembled composite of V-Ga filament rods in the Cu-Ga matrix billet, in the foreground, shows an effort to strengthen the wire with a central Ti-alloy strand. In the background are swaged rods and coils of drawn wire of 30-filament material — intermediate products in producing superconducting wires. Scale: approx. 1:1. (The Cu-Ga billet is 24 mm in diameter.)



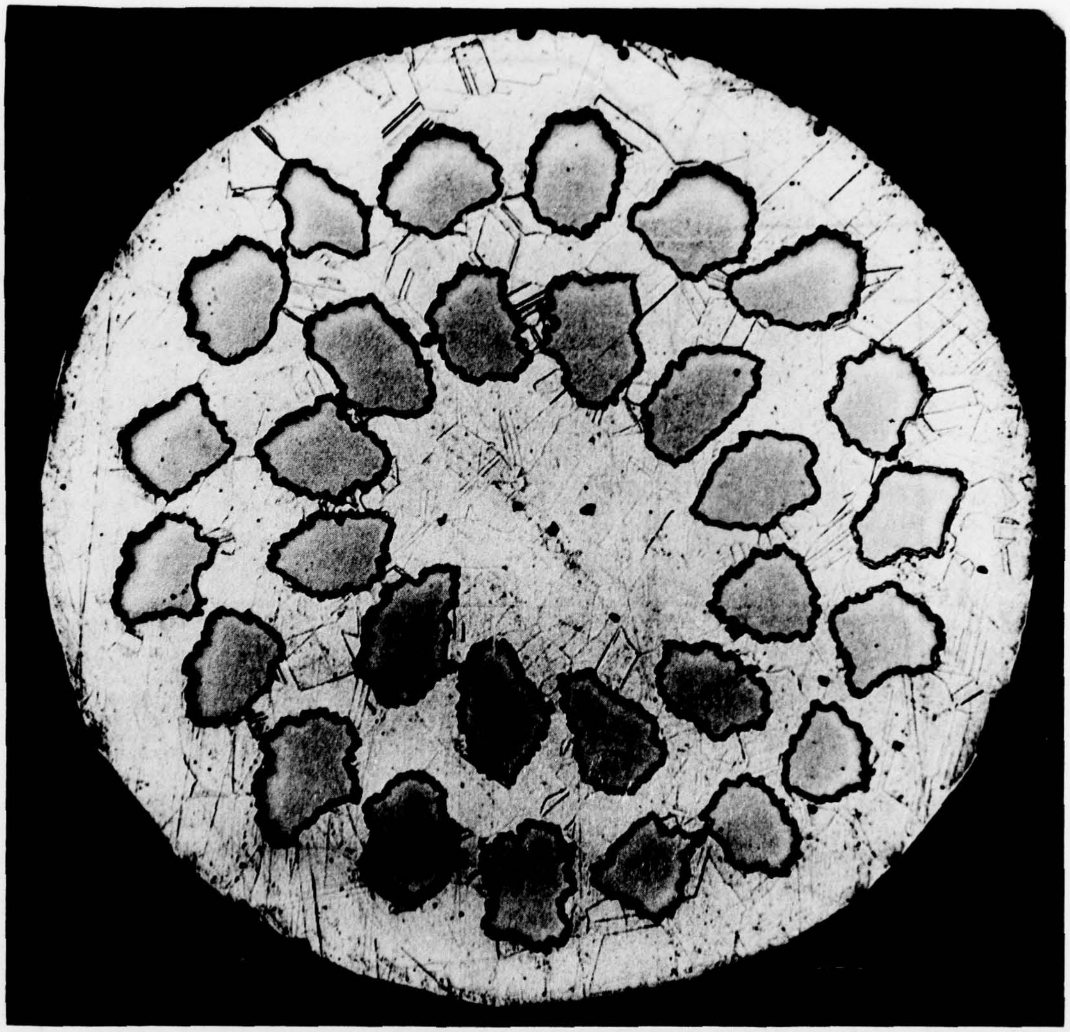


Fig. 4 – Micrograph of the cross-section of a 0.8 mm diameter wire containing 30-filaments of V-8 at % Ga in a Cu-17.5 at % Ga matrix. A 144 hour heat-treatment at 650° has produced the 4 μm thick layer of V_3Ga on each of the filaments. Marker = 50 μm.

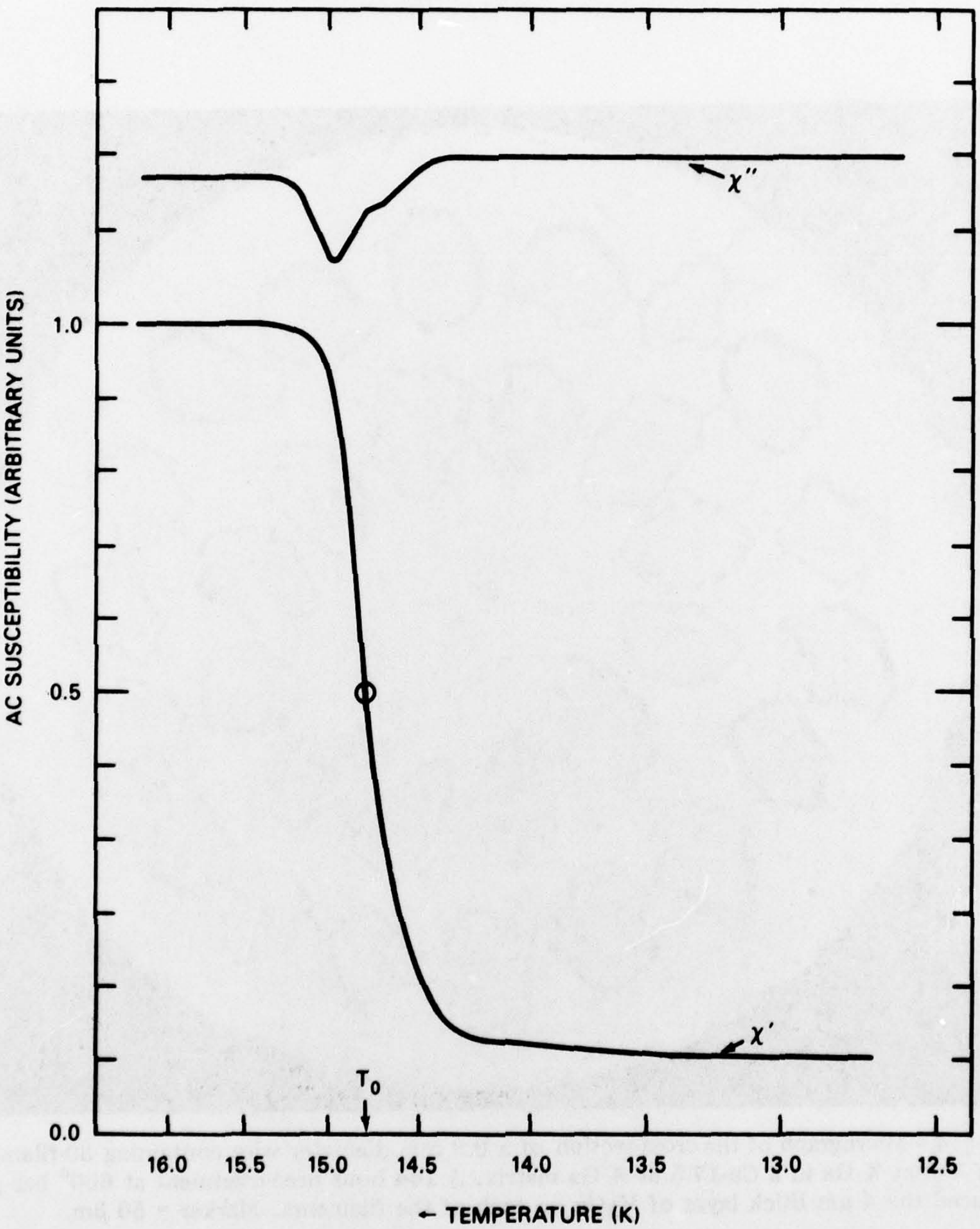


Fig. 5 - In-phase, χ', and out-of-phase, χ'', components of the ac magnetic susceptibility as a function of temperature. The temperature at which $\chi' = 0.5$ is the transition temperature, T_O.

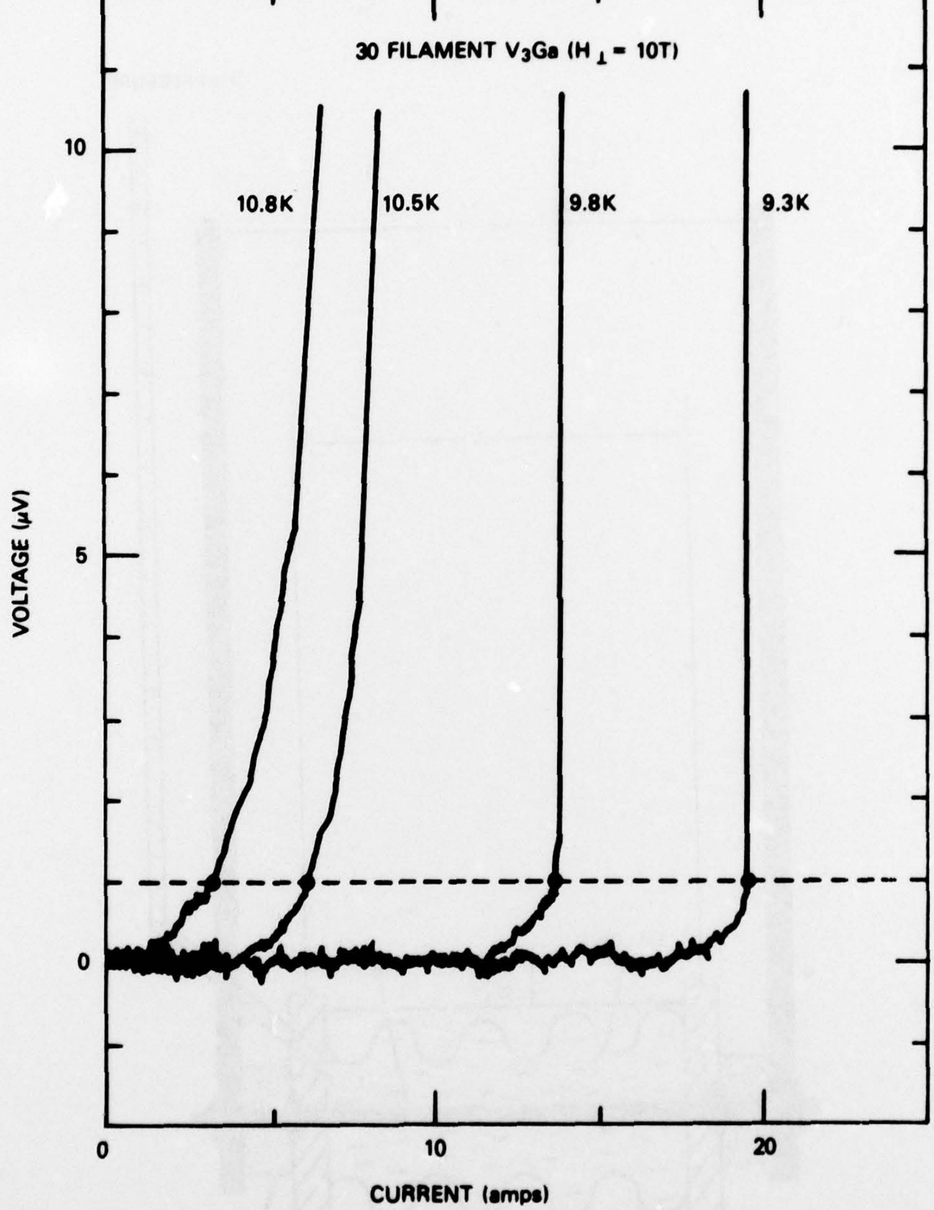


Fig. 6 - Voltage versus current characteristics of a V_3Ga wire at four temperatures in a transverse magnetic field of 10T. The intersections of these traces with the dashed-line at $1\mu V$ ($2\mu V/cm$) are the I_c's of the wire at the respective temperatures.

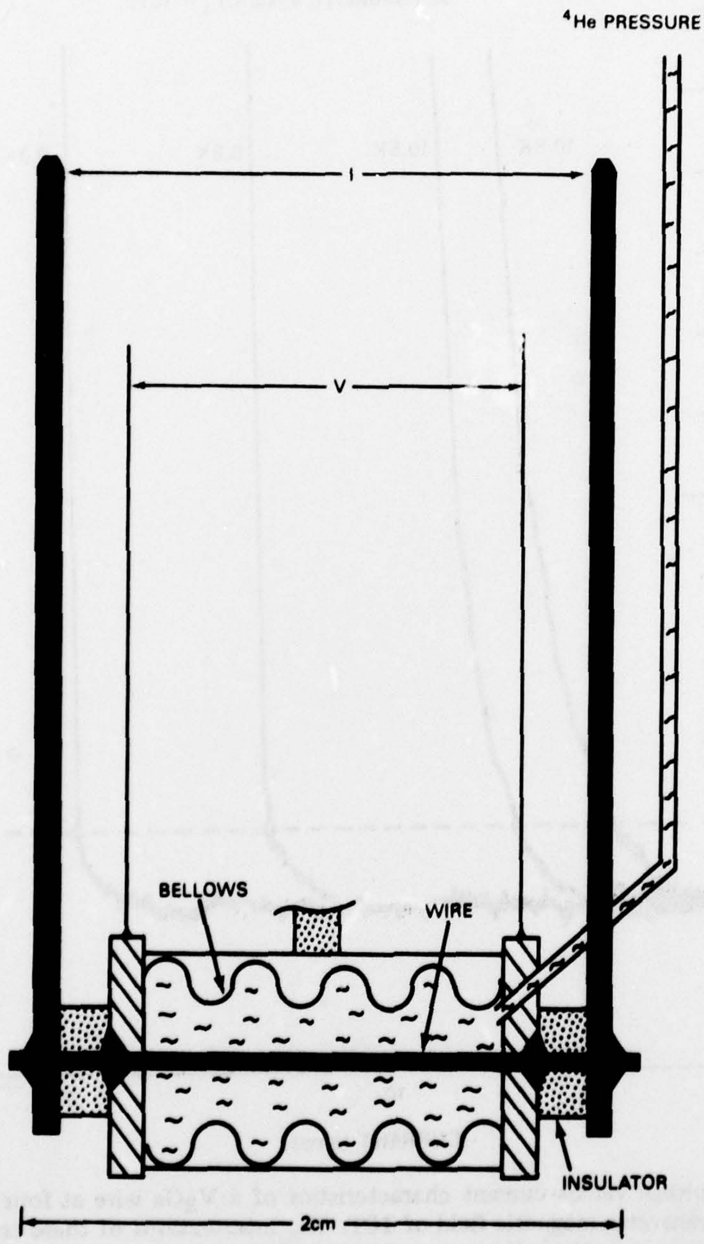


Fig. 7 - Schematic of stress-cryostat

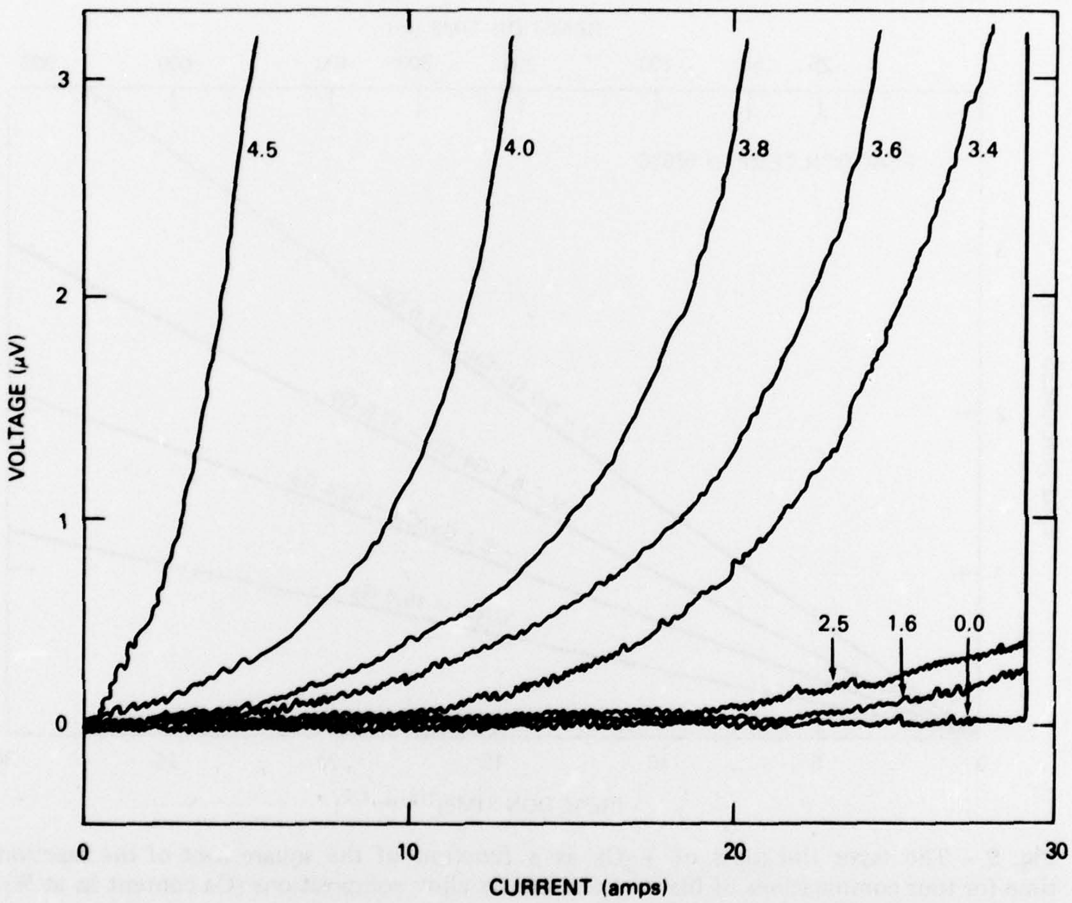


Fig. 8 - Voltage versus current characteristics of a V_3Ga wire at tensile stresses of 0.0 to 4.5×10^8 Pa (0 to 65,250 psi). The magnetic field and temperature were constant: 9T and 4.2K respectively.

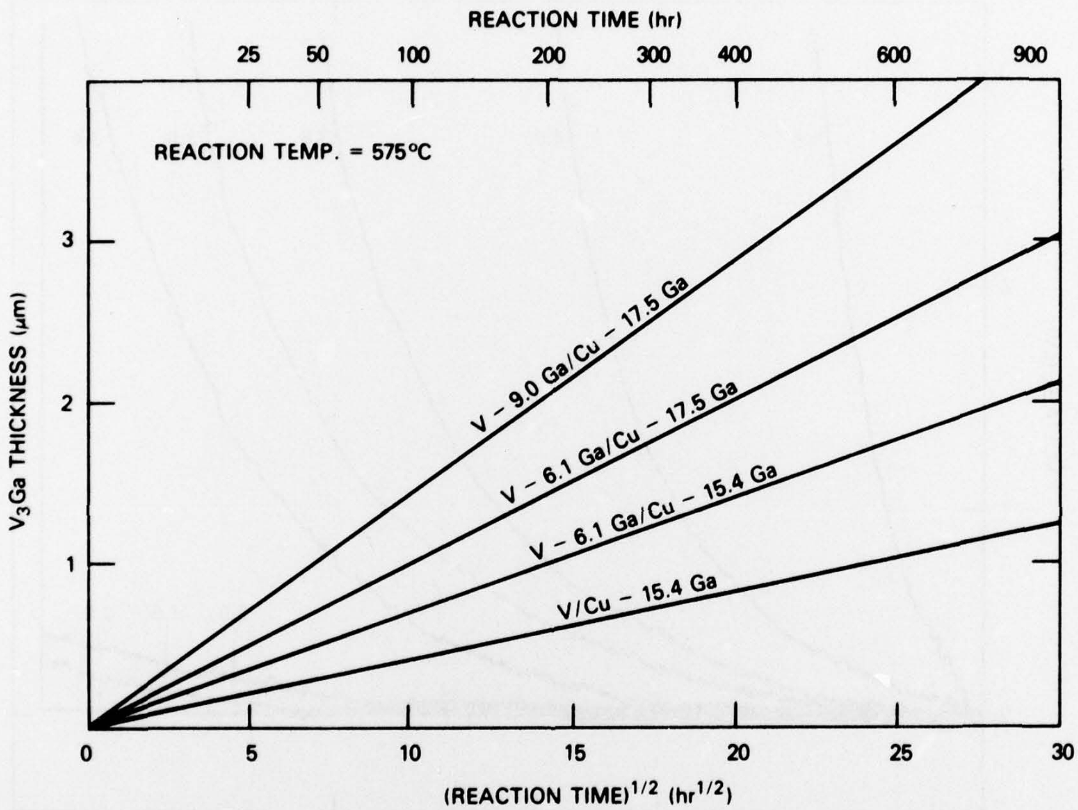


Fig. 9 - The layer thickness of V_3Ga as a function of the square root of the reaction time for four combinations of filament and matrix alloy compositions (Ga content in at %). The reaction temperature is 575°C.

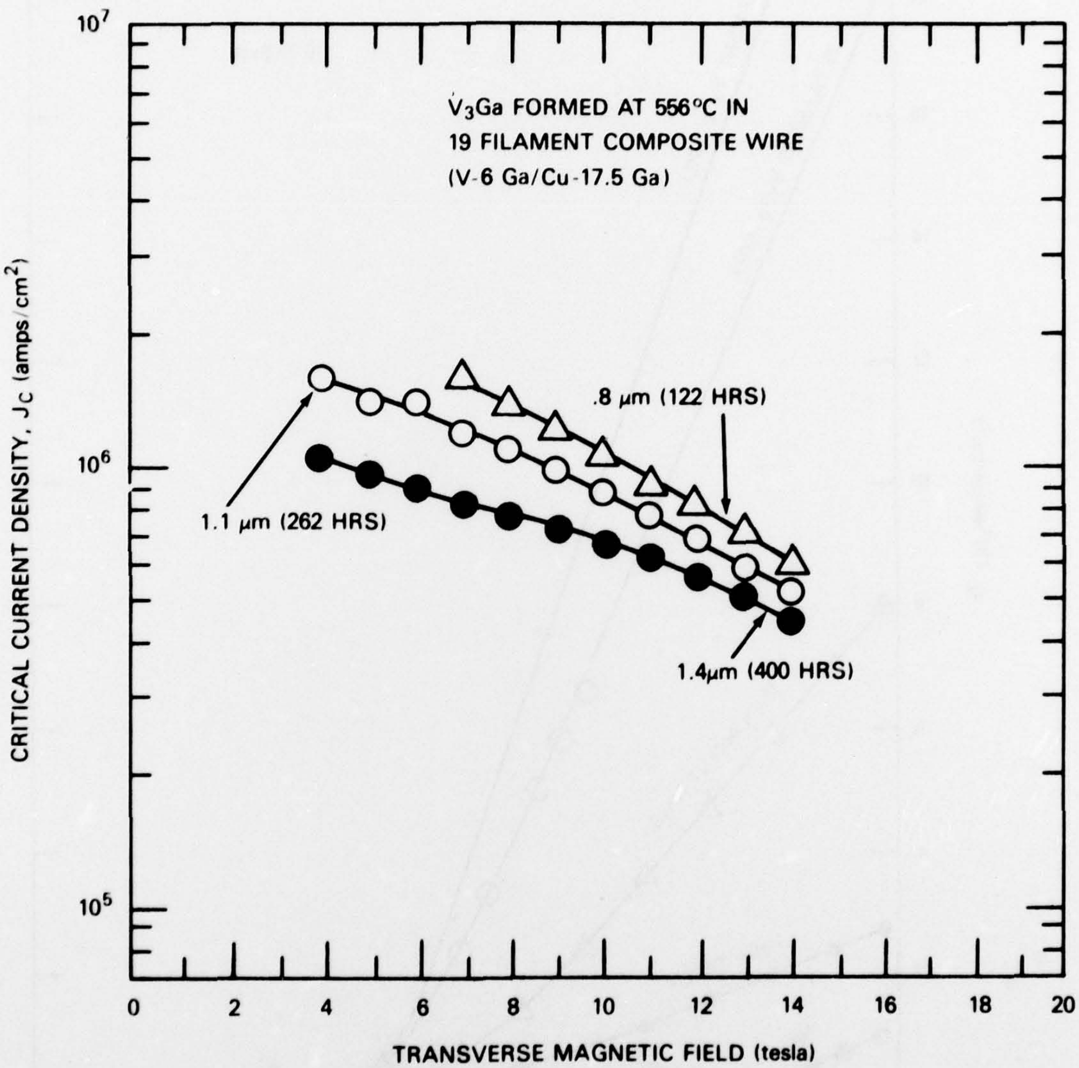


Fig. 10 - Critical current density, J_C, as a function of the transverse magnetic field for three V_3Ga layer thicknesses at 4.2K.

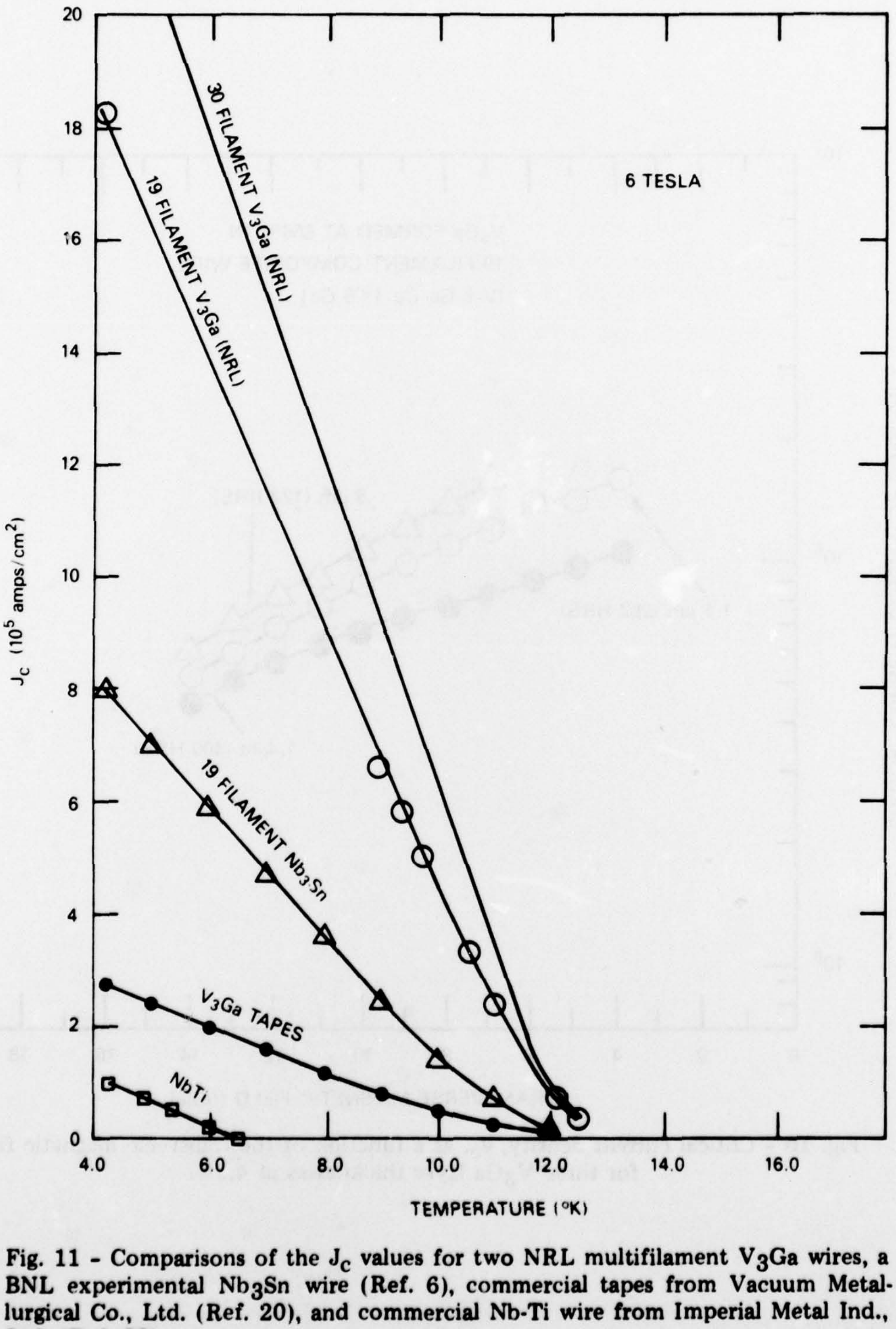


Fig. 11 - Comparisons of the J_c values for two NRL multifilament V_3Ga wires, a BNL experimental Nb_3Sn wire (Ref. 6), commercial tapes from Vacuum Metallurgical Co., Ltd. (Ref. 20), and commercial Nb-Ti wire from Imperial Metal Ind., Ltd. (Ref. 20).

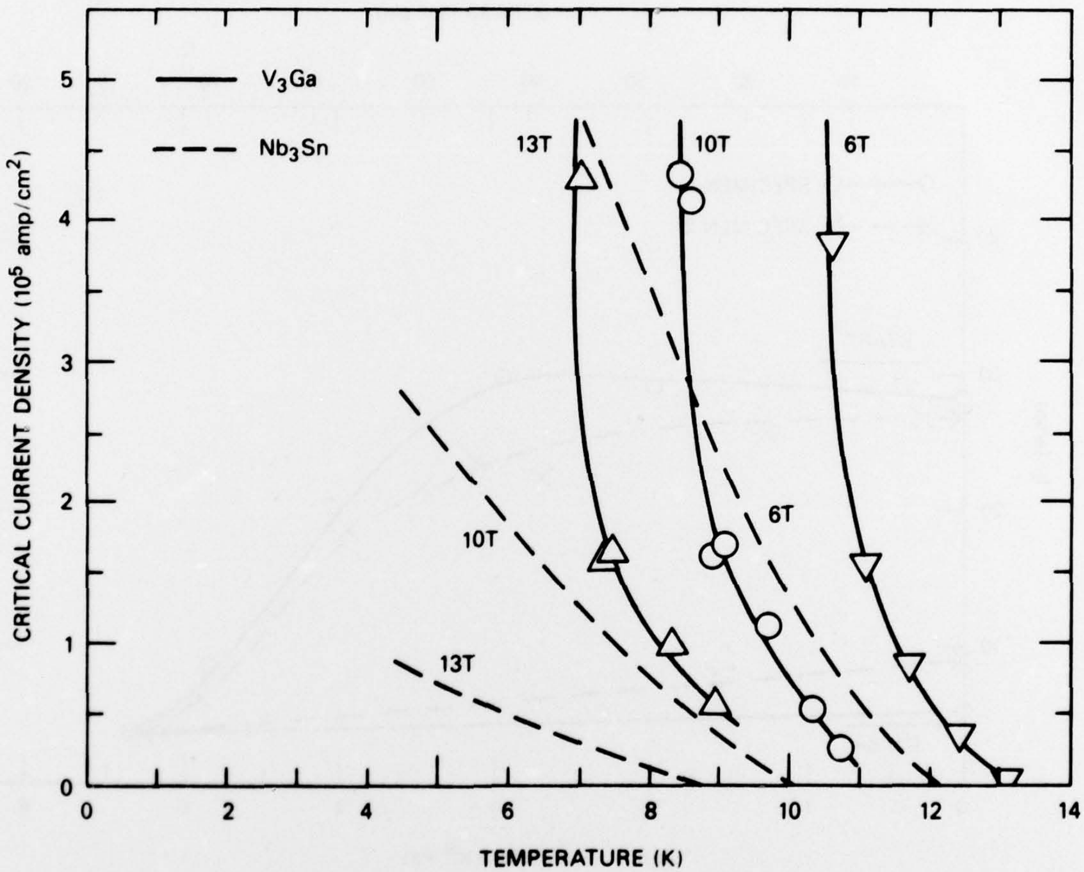


Fig. 12 - Comparisons of the critical current density of V_3Ga and Nb_3Sn as a function of temperature in transverse magnetic fields of 6, 10, and 13T. Nb_3Sn data from Ref. 6.

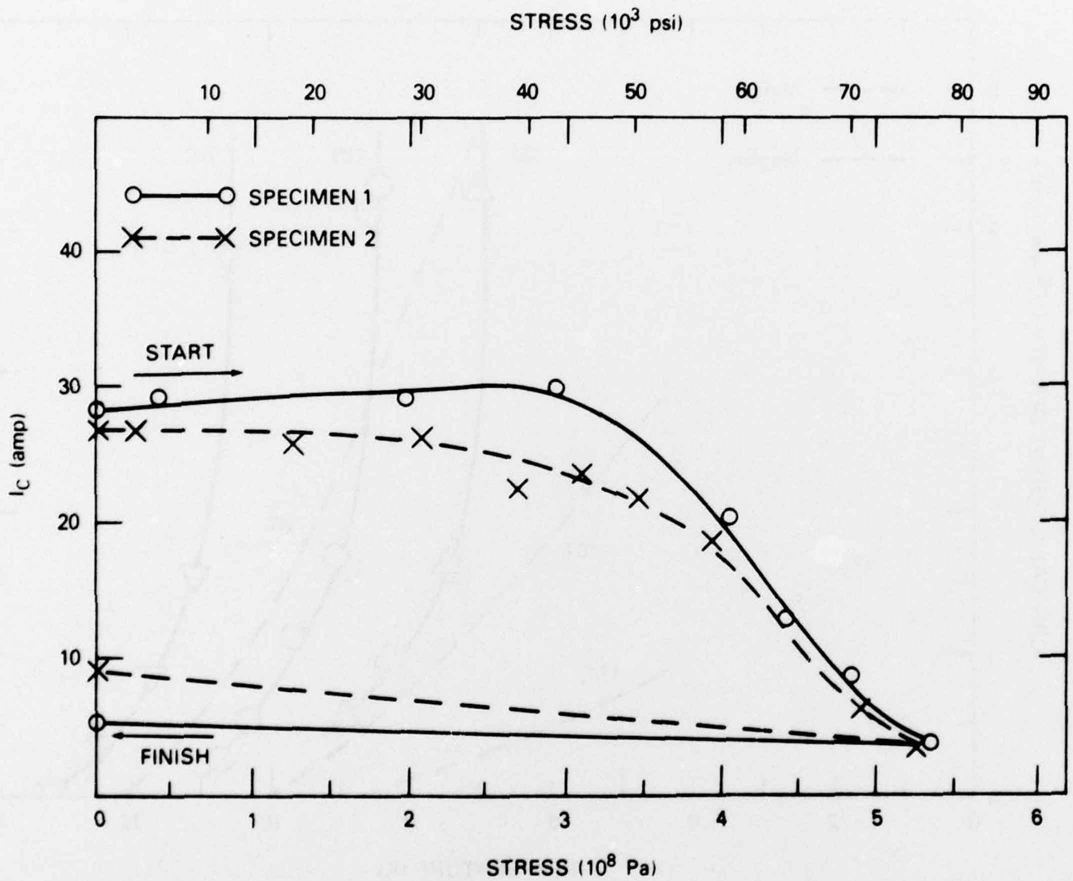


Fig. 13 - Critical current as a function of tensile stress for two specimens of 30-filament wire (V-8 at % Ga/Cu-17.5 at % Ga) reacted at 556°C for 116 h to produce 0.85 μm layers of V_3Ga. Test conditions: 4.2K, 9T, E-field criterion of 0.74 μV/cm.